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Monthly-averaged hourly solar diffuse radiation models for world-wide locations

T. Muneer[1], EJ Gago[2*] and S. Etxebarria[2]

Abstract

Monthly-averaged daily global irradiation data are now easily available from NASA website for any global location. Using established models it is then possible to decompose the daily to averaged-hourly global irradiation. The missing link so far has been hourly averaged diffuse irradiation. In this article data was pooled from 14 world-wide locations to obtain a regression model to complete the above missing link. It was presently shown that the averaged–data regressions are distinctly different from previously available hour-by-hour regressions.

Keywords: Solar radiation; Averaged-hourly solar diffuse fraction; Insolation; Solar diffuse radiation

Introduction

Solar radiation data are essential for the design of very many energy systems. These data are needed for obtaining solar energy resource assessment, its transmission and also to obtain the efficiency of energy delivery. A few examples are solar water heating, and space PV systems, daylighting, building air conditioning load and solar-driven ventilation. The starting point for the above computational chain is almost always global and diffuse horizontal radiation. Usually, the computations are carried out using hourly or sub-hourly data.

Note that not always it is possible to obtain a long-term series of hourly or sub-hourly data for the above parameters.

The most commonly measured solar data are global irradiation and these are available for a limited number of stations within any given country at an hourly, daily or monthly frequency. For example within the UK and Spain a historical records of hourly data are available for 71 and 31 stations, respectively.

Of these stations due to higher operational costs associated with diffuse radiation measurements the respective meteorological offices tend to record the latter variable at much fewer locations. For example, since the year 2002 within the UK the diffuse radiation is recorded at only two locations, at North latitudes of Camborne (50.21°) and Lerwick (60.80°).

On the contrary, through the work of NASA (http://eosweb.larc.nasa.gov/cgi-bin/sse/retscreen.cgi?email=rets@nrcan.gc.ca) it is now possible to obtain daily-averaged irradiation data for virtually any location in the world. A sample table of climatic data for Easthampstead (Bracknell) is provided in Table 1.

This information was downloaded from the above-mentioned NASA website. The NASA reported irradiation data were compared by the present research team against averaged measured data for one UK location for the period 1981–1983 (three complete years) (see Fig. 1). The statistics within the latter figure shows that there is a close concordance between the satellite-based NASA irradiation and the UK Meteorological Office measured data set.

Following the original work of Liu and Jordan (Liu & Jordan 1960) a great many number of research teams from around the world have produced regressions relating diffuse ratio (k) and clearness index (kt) regressions at an hourly, daily, monthly and annual frequency. Each of the above four category of regression is unique and statistically different as shown in the work of Muneer (Muneer 2004) and Saluja et al. (Saluja et al. 1988).

The present article was pooled from 14 world-wide locations to obtain a regression model to complete the above missing link. It was presently shown that the averaged–data based regressions are distinctly different from previously available hour-by-hour regressions.

* Correspondence: ejadraque@ugr.es
[2]University of Granada, Granada, Spain
Full list of author information is available at the end of the article

Table 1 Climatic data for Easthampstead (Bracknell) with the NASA reported irradiation data and averaged measured data for the period 1981-1983

	Unit	Climate data location							
Latitude	°N	51,42							
Longitude	°E	−0,75							
Elevation	m	58,00							
Heating design temperature	°C	−1,74							
Cooling design temperature	°C	22,96							
Earth temperature amplitude	°C	14,35							
Frost days at site	day	37,00							
Month	Air temperature	Relative humidity	Daily solar radiation-horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days	Average measured radiation
	°C	%	kWh/m^2/day	kPa	m/s	°C	°C-d	°C-d	kWh/m^2/day
January	4,2	83,90	0,77	100,8	6,3	3,1	426	1	0,71
February	4,3	80,20	1,39	101,0	5,8	3,6	380	1	1,28
March	6,4	76,80	2,34	100,9	6,0	6,2	353	4	2,18
April	8,6	69,80	3,59	100,7	5,1	9,1	279	21	3,55
May	12,7	64,00	4,57	100,9	4,7	13,8	168	92	4,11
June	16,1	60,80	4,84	100,9	4,4	17,7	75	177	4,86
July	18,6	60,20	4,80	100,9	4,4	20,4	25	261	4,77
August	18,6	61,20	4,23	100,9	4,3	20,3	26	264	4,23
September	15,5	66,30	2,86	100,9	5,0	16,5	83	164	2,85
October	11,7	74,10	1,73	100,7	5,5	11,5	191	73	1,57
November	7,3	83,20	0,96	100,7	5,9	6,4	318	11	0,80
December	4,9	85,00	0,60	100,8	6,1	3,8	404	3	0,60
Annual									
	10,7	72,10	2,72	100,8	5,3	11,0	2728	1072	
Measured at (m)					10,0	0,0			

Website: http://eosweb.larc.nasa.gov/cgi-bin/sse/retscreen.cgi?email=rets@nrcan.gc.ca

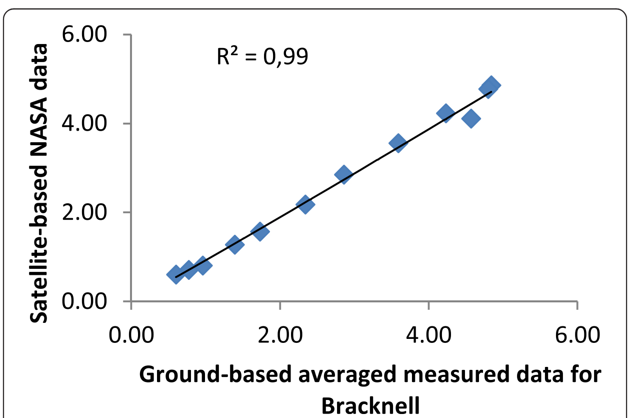

Fig. 1 Comparison between NASA reported irradiation data and ground-based averaged measured data for Bracknell, kWh/m^2-day

The unique nature of solar radiation regressions

Historically speaking, a large number of research teams from around the world have produces k-kt regressions that were based on an hour-by-hour, daily, monthly or annual data. Examples that may be cited here, are Liu and Jordan (daily, and monthly-averaged daily) (Liu & Jordan 1960), Erbs et al. (hourly, daily and monthly-averaged daily) (Erbs et al. 1982), Hawas and Muneer (hour-by-hour, daily, monthly- and annual-averaged daily) (Hawas & Muneer 1984; Muneer & Hawas 1984; Muneer et al. 1984) and Stanhill (monthly- and annual-averaged daily) (Stanhill 1966).

Presently, Figs. 2 and 3 show the unique nature of hour-by-hour (Fig. 2: $k - k_t$ plot) and monthly-averaged hourly regressions (Fig. 3: $\bar{k}-\bar{k}_t$). An important point to note is that while Fig. 2 shows a convex profile, Fig. 3

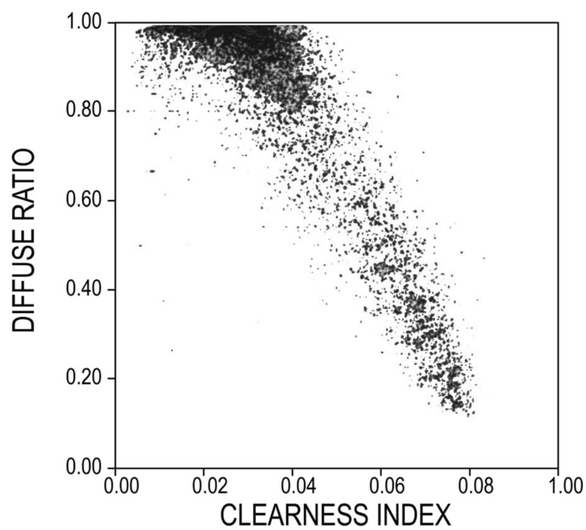

Fig. 2 Hourly diffuse ratio versus clearness index for UK locations

demonstrates a concave behaviour. The latter two figures are based on data from common UK locations.

While there are established models for data of Fig. 2 there are no regressions available in literature for averaged-hourly data such as those shown in Fig. 3. The object of this article is to present the latter type of regressions.

Presently developed monthly-averaged hourly $\bar{k}-\bar{k}_t$ regressions

Fourteen worldwide locations were chosen for this study, details of which are shown in Table 2.

Data consisted of hourly global and diffuse irradiation values for several years for each location, covering most of the range of latitude for the country. The location names have been arranged in an increasing order of latitude.

Monthly-averaged hourly values were calculated for the global and diffuse radiation considering the data period for each location. For each of them, the monthly-averaged hourly diffuse ratio $(\bar{k})$ and the corresponding clearness index $(\bar{k}_t)$ were calculated from sunrise to sunset. The following conditions were used in each case to remove erroneously recorded data.

$$k_T = \frac{I_G}{I_E} \rightarrow I_G < I_E \qquad (1)$$

$$k = \frac{I_D}{I_G} \rightarrow I_D \leq I_G \qquad (2)$$

The monthly-averaged clearness index was then regressed against the monthly-averaged diffuse ratio for each location. Figure 4 shows one such scatter plot for Chennai and Lisbon. Furthermore, for each increment at bandwidth of clearness index of 0.05 width, the corresponding values of averaged diffuse ratio shown in Fig. 5 were obtained, shown here for pooled data from two Indian locations.

Figures 6 and 7 respectively show the regressions for locations in a narrower range of latitudes (20-42° N) and worldwide sites with a more diverse range of latitudes (13-58°N).

Note that Fig. 6 shows the potential for a single regression model. Figure 7 on the other hand indicates the existence of different sub-models and these shall now be explored further.

Figures 8, 9 and 10 respectively present regressions models that were obtained by pooling data from locations with a latitude range of 13-20° N, 20-42° N and 50-58° N.

Table 3 presents regressions equations and coefficient of determination (R^2) for each location.

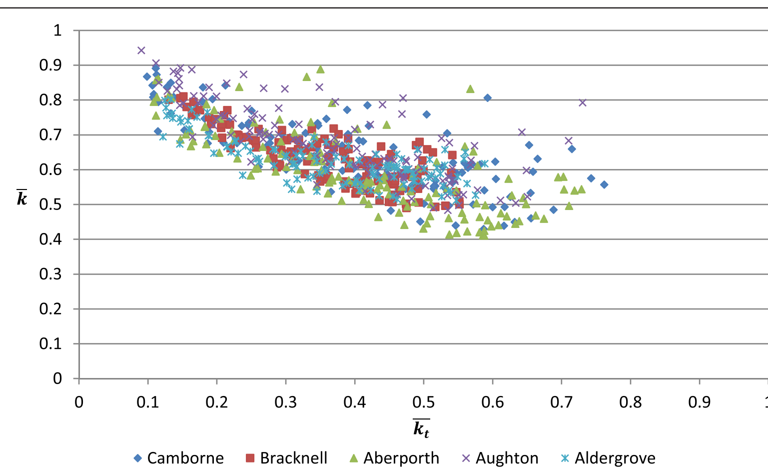

Fig. 3 Monthly-averaged hourly plot for UK locations (arranged in an increasing order of latitude: Camborne 50.21° N, Aldergrove 54.65° N)

Table 2 The 14 worldwide locations that were presently investigated

Country	Location	Latitude	Longitude	Period of observation
India	Chennai	13.08	80.18	1990–1994
	Pune	18.32	73.85	1990–1994
Kingdom of Bahrain	Bahrain	26.03	50.61	2000–2002
State of Kuwait	Kuwait	29.22	47.98	1996–2000
Spain	Almeria	36.83	−2.38	1993–1998
Portugal	Faro	37.02	−7.96	1982–1986
	Lisbon	38.71	−9.15	1982–1990
Spain	Madrid	40.40	−3.55	1999–2001
	Girona	41.97	2.76	1995–2001
United Kingdom	Camborne	50.21	5.30	1981–1995
	Bracknell	51.42	0.75	1992–1994
	Aberporth	52.13	4.55	1975–1995
	Finningley	53.48	0.98	1982–1995
	Stornoway	58.22	6.39	1982–1995

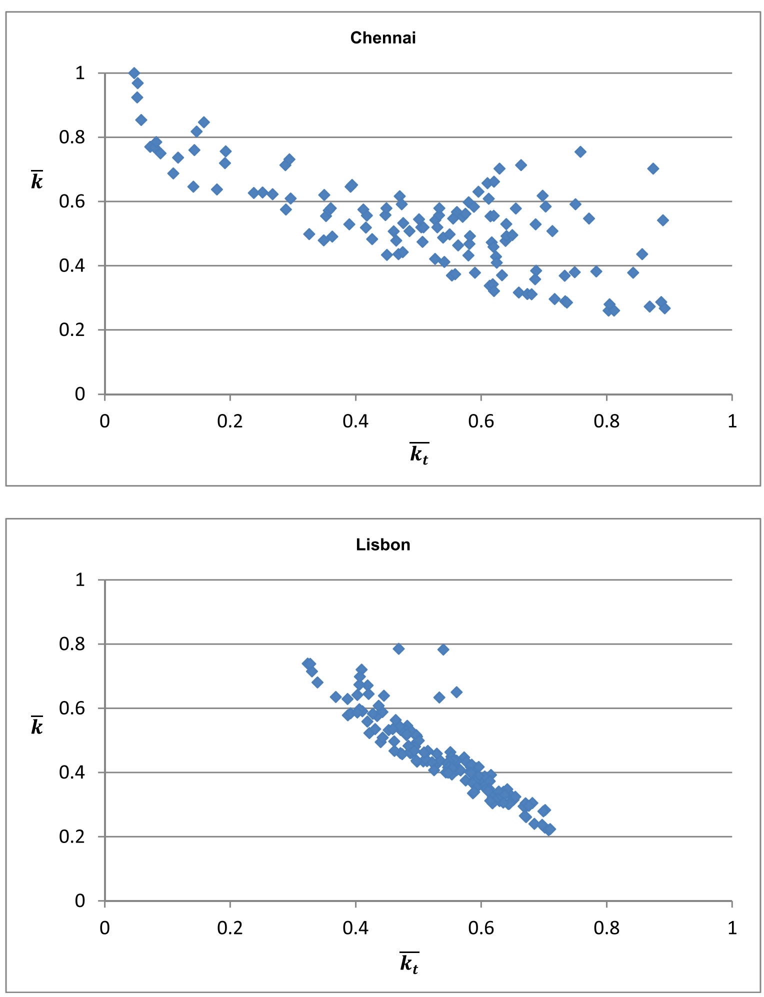

Fig. 4 Monthly-averaged hourly diffuse ratio (y-axis) versus clearness index (x-axis) fot two locations. One Indian and other a South European

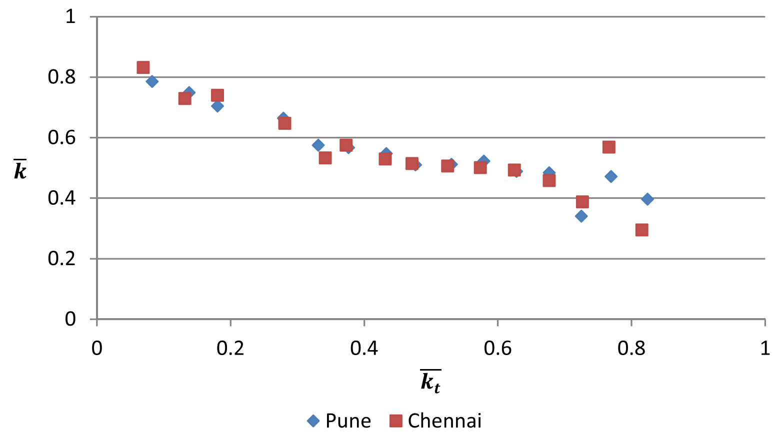

Fig. 5 Averaged values of diffuse ratio for the locations between latitude 13-20° North

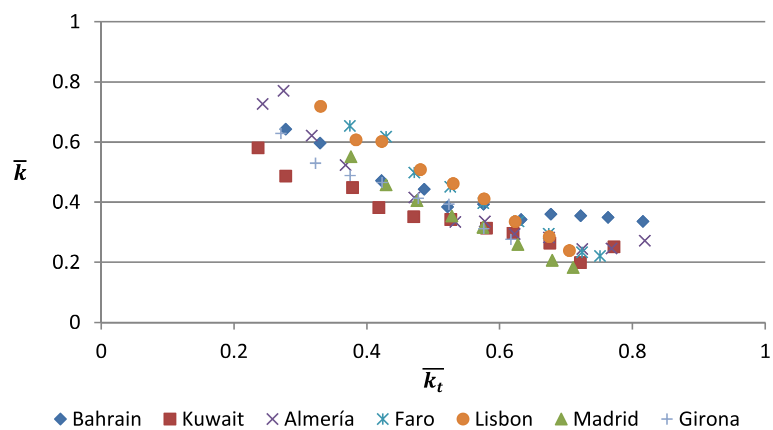

Fig. 6 Averaged values of diffuse ratio for the locations between latitude 20-42° North

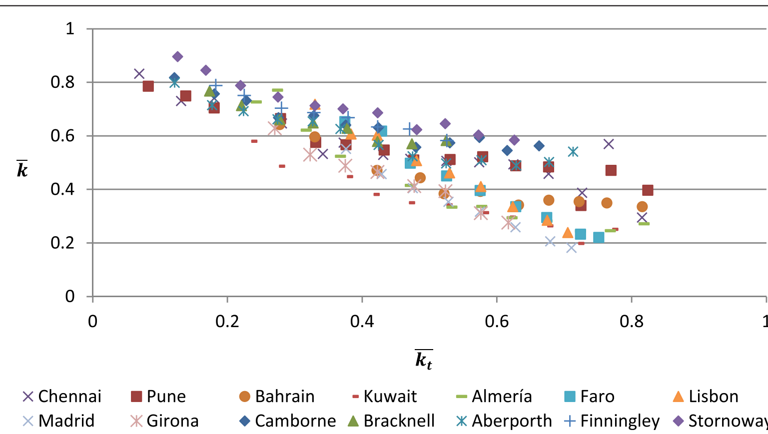

Fig. 7 Averaged values of diffuse ratio for the all locations

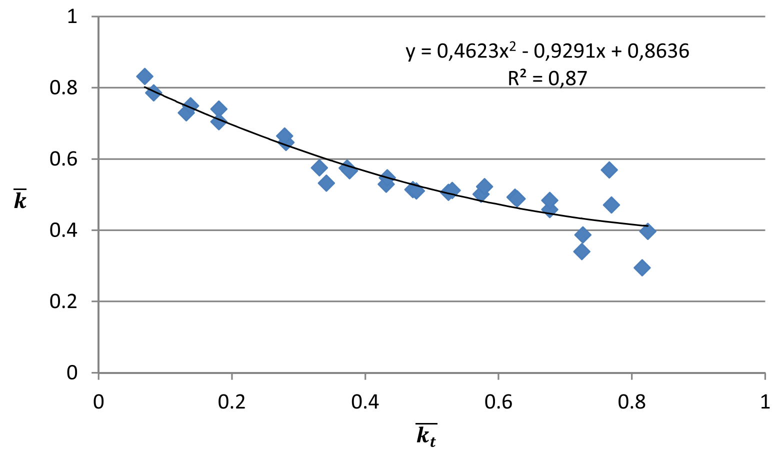

Fig. 8 Averaged values of diffuse ratio for the locations between latitude 13-20° North (Chennai and Pune)

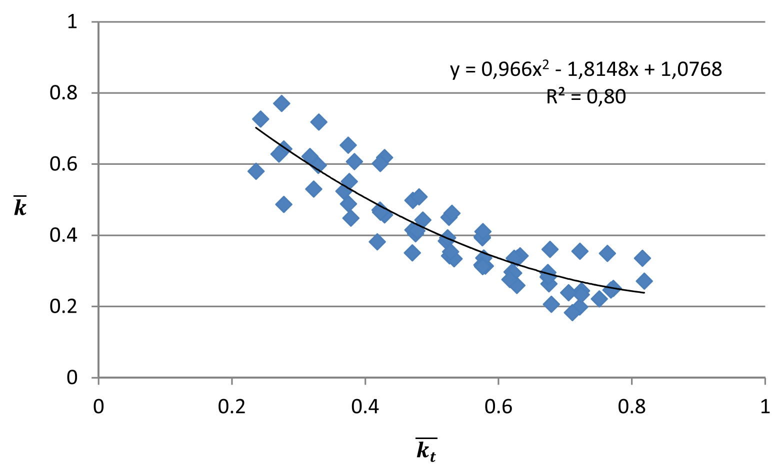

Fig. 9 Averaged values of diffuse ratio for the locations between latitude 20-42° North (Bahrain, Kuwait, Almeria, Faro, Lisbon, Madrid and Girona)

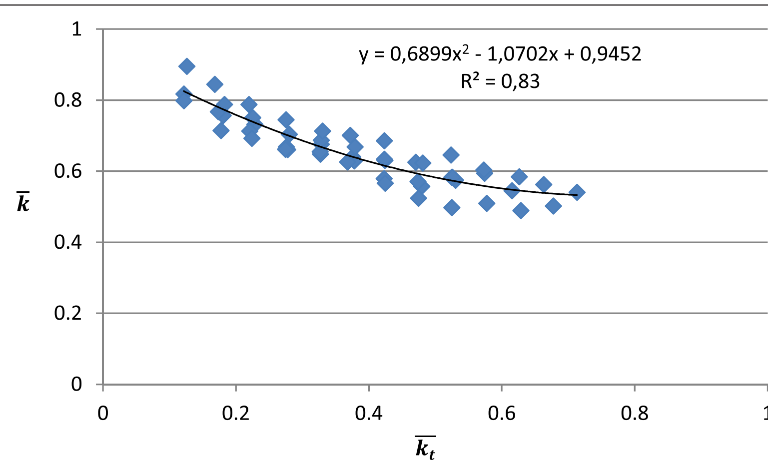

Fig. 10 Averaged values of diffuse ratio for the locations between latitude 50-58° North (Camborne, Bracknell, Aberporth, Finningley and Stornoway)

Table 3 The regressions equations and coefficient of determination (R^2) for each location

Country	Location	Regression equations	R^2
India	Chennai	$y = 0.5124x^2 - 0.9809x + 0.8733$	0.83
	Pune	$y = 0.4083x^2 - 0.873x + 0.853$	0.92
Kingdom of Bahrain	Bahrain	$y = 1.4455x^2 - 2.113x + 1.1262$	0.98
State of Kuwait	Kuwait	$y = 0.7088x^2 - 1.3237x + 0.8299$	0.96
Spain	Almeria	$y = 1.9414x^2 - 2.9329x + 1.3637$	0.98
Portugal	Faro	$y = 0.9184x^2 - 2.2173x + 1.3654$	0.99
	Lisbon	$y = 0.0721x^2 - 1.3001x + 1.1246$	0.99
Spain	Madrid	$y = 0.9087x^2 - 2.0465x + 1.1808$	0.99
	Girona	$y = 0.1781x^2 - 1.0867x + 0.887$	0.98
United Kingdom	Camborne	$y = 0.8188x^2 - 1.1127x + 0.9365$	0.96
	Bracknell	$y = 1.4394x^2 - 1.5414x + 0.9878$	0.97
	Aberporth	$y = 0.9797x^2 - 1.3032x + 0.9403$	0.95
	Finningley	$y = 0.451x^2 - 0.876x + 0.9267$	0.99
	Stornoway	$y = 7441x^2 - 1.1382x + 1.0147$	0.98

Three points are worthy of note from Figs. 8, 9 and 10:

i. A strong correlation is observed between $\bar{k}$ and $\bar{k}_t$ with the respective coefficient of determination of 0.87, 0.80 and 0.83 (corresponding values of coefficient of correlation are 0.93, 0.89 and 0.91),
ii. In each case the shape of the regressed curve is concave, contrary to the convex profile for hour-by-hour regressions reported by research teams from around the world, and
iii. it is not possible to produce a single regressed curve for worldwide locations.

The latter point is reinforced via Fig. 11.

Conclusions

Monthly-averaged daily global irradiation data are now easily available from NASA website for any terrestrial location. Using established models such as those presented by Liu and Jordan (Liu & Jordan 1960), Collares-Pereira and Rabl (Collares-Pereira & Rabl 1979), Mani and Rangarajan (Mani & Rangarajan 1983), Muneer and Saluja (Muneer & Saluja 1996) and Lloyd (Lloyd 1982) it is then possible to decompose the daily–to averaged-hourly global irradiation. The missing link so far has been hourly averaged diffuse irradiation. The authors report a regression model to complete the above missing link for 14 world locations and show that the averaged–data regressions are distinctly different from previously available hour-by-hour regressions.

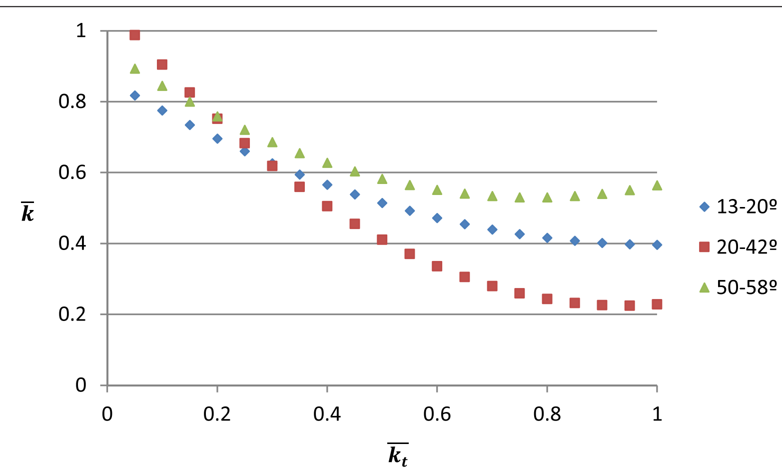

Fig. 11 Monthly-averaged hourly regressions for three ranges of latitudes

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
Authors made substantial contributions to conception and design, and acquisition of data, and analysis and interpretation of data. Authors participated in drafting the article and revising it critically for important intellectual content. Authors give final approval of the version to be submitted and any revised version.

Author details
[1]Edinburgh Napier University, Edinburgh, UK. [2]University of Granada, Granada, Spain.

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